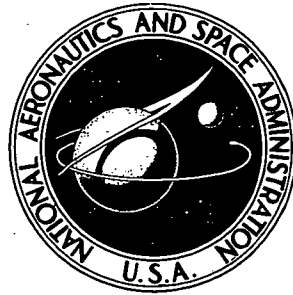


N72-31552

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HOT PRESS AND ROLL WELDING
OF TITANIUM - 6-PERCENT-ALUMINUM -
4-PERCENT-VANADIUM BAR AND SHEET
WITH AUTO-VACUUM CLEANING

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1972

1. Report No. NASA TN D-6958		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle HOT PRESS AND ROLL WELDING OF TITANIUM - 6-PERCENT-ALUMINUM - 4-PERCENT-VANADIUM BAR AND SHEET WITH AUTO-VACUUM CLEANING				5. Report Date September 1972	
				6. Performing Organization Code	
7. Author(s) Kenneth H. Holko				8. Performing Organization Report No. E-6997	
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135				10. Work Unit No. 114-03	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				13. Type of Report and Period Covered Technical Note	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract <p>Hot press butt welds were made in 13 millimeter (0.5 in.) diameter bar, and roll lap welds were made in 1.6 millimeter (0.060 in.) thick sheet of Ti-6Al-4V. For hot press welds made after auto-vacuum cleaning at 980° C (1800° F) for 2 hours, weld strength and ductility equaled the parent metal properties. Only 5 minutes of pressing time were needed at 980° C (1800° F) and 1.38 MN/m² (200 psi) to make the hot press welds. Roll welds were made in sheet at 955° C (1750° F) with only 10 percent deformation. The welds in the bar and sheet were metallurgically indistinguishable from the parent material.</p>					
17. Key Words (Suggested by Author(s)) Ti-6Al-4V Hot press welding Roll welding Auto-vacuum cleaning				18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 25	
				22. Price* \$3.00	

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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CONTENTS

	Page
SUMMARY	1
INTRODUCTION	2
MATERIALS AND PROCEDURE	3
Materials and Specimen Preparation	3
Auto-Vac Cleaning Procedure	3
Solid-State Welding Procedure	5
Hot press butt welding	5
Roll welding	6
Evaluation Procedures	6
Mechanical testing	6
Metallography	7
RESULTS AND DISCUSSION	8
Mechanical Properties	8
Metallography	10
Hot press butt welds in bar	11
Roll welded sheet	16
CONCLUDING REMARKS	21
SUMMARY OF RESULTS	21
REFERENCES	22

HOT PRESS AND ROLL WELDING OF TITANIUM - 6-PERCENT- ALUMINUM - 4-PERCENT-VANADIUM BAR AND SHEET WITH AUTO-VACUUM CLEANING

by Kenneth H. Holko
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SUMMARY

Hot press butt welds were made in 13 millimeter (0.5 in.) diameter Ti-6Al-4V bar, and roll lap welds were made in 1.5 millimeter (0.060 in.) thick Ti-6Al-4V sheet. The faying surfaces of all weld specimens were seal-welded at their peripheries prior to either hot press or roll welding. Some of the weld specimens were also given an auto-vacuum cleaning treatment at 980°C (1800°F) before welding. The auto-vacuum cleaning treatment dissolved the oxides from the faying surfaces into the parent material. Solid-state welding occurred when the mating surfaces were brought into contact. Weld specimens were evaluated metallographically and by room temperature tensile testing.

Excellent hot press butt welds were produced in Ti-6Al-4V bar by first auto-vacuum cleaning at 980°C (1800°F) for 2 hours and then hot pressing at 955°C (1750°F) for 5 minutes with a pressure of 1.38 MN/m^2 (200 psi). The time required for welding (5 min) was greatly reduced from conventional diffusion welding practice (60 to 180 min) due to the prior auto-vacuum cleaning treatment. A deformation of about 1/2 percent took place at the weld. Metallographic examination showed that grain growth across the weld line eliminated all evidence of the weld interface. Room temperature tensile tests of the butt welds resulted in parent metal strength and ductility. It was also found that while strength values for poor-quality solid-state welds could be high, the elongation and reduction in area values were invariably low. But in high-quality welds, the ductility values were also high. Thus, it is apparent that both strength and ductility values must be considered in judging weld quality.

High-quality roll welds were made in Ti-6Al-4V sheet with as little as 10-percent deformation at 955°C (1750°F). This was an improvement over the 60-percent deformation commonly used. The auto-vacuum cleaning treatment was not necessary to achieve this result, although the seal weld was. It is felt that the auto-vacuum phenomenon occurred during heat-up to the rolling temperature, during rolling, and during cool-down from the rolling temperature.

INTRODUCTION

The purpose of this work was to apply the "auto-vacuum cleaning" technique (refs. 1 and 2) to the Ti-6Al-4V* alloy, and thereby improve upon current solid-state welding technology for this alloy. Current hot press welding practices for Ti-6Al-4V involve long welding times, typically 60 to 180 minutes, to dissolve oxides present at the faying surfaces (refs. 3 to 5) and to produce a weld. Roll welding Ti-6Al-4V requires large deformations, typically 60 percent, to break-up oxide films, and to allow their dissolution (ref. 6). It was the intent of this study to reduce the required welding time for hot press welding and the deformation required for roll welding by auto-vac cleaning prior to welding.

The auto-vac cleaning technique is described in detail in reference 1. Briefly, this cleaning technique involves first seal welding the two pieces to be solid-state welded at the periphery of their faying surfaces. The assembly is then heated to a temperature high enough to cause the oxides on the faying surfaces to be dissolved in the parent material. Any gases present between the faying surfaces are also dissolved in the parent material, and a vacuum is created (thus, the term "auto-vac"). Since the faying surfaces are sealed from the atmosphere, no oxygen is available to reform the oxides. The faying surfaces are now clean and free of oxides and can be brought into intimate contact to produce metallic bonds across the interface.

In the Soviet Union, the auto-vac cleaning technique is being used in the production of iron-base roll-clad sheet metal (ref. 7). In the United States, the seal welding aspect of the auto-vac cleaning technique has been used on large Ti-6Al-4V parts that are forge welded (ref. 8). In the latter case, the seal welding is done to facilitate handling of the parts and to prevent excessive oxidation from occurring at the faying surfaces during heating to the forging temperature.

Two solid-state welding processes were investigated in this study: hot press butt welding and roll lap welding. Hot press butt welding represented a low deformation process (about 1/2 percent), and roll welding represented a high deformation process (10 to 50 percent). Ti-6Al-4V bar, 13 millimeters (0.5 in.) in diameter was hot press butt welded in a vacuum hot press. Also, 1.6 millimeter (0.060 in.) thick Ti-6Al-4V sheet was roll welded. Both types of specimens were solid-state welded with and without prior auto-vac cleaning. The effects of these and other welding parameters were evaluated by room temperature tensile tests and light microscopy.

*Compositions are in weight percent.

MATERIALS AND PROCEDURE

Materials and Specimen Preparation

Both bar and sheet material were prepared for solid-state welding as shown in figure 1. The nominal chemical composition of the commercially produced bar and sheet is Ti-6Al-4V. Both types of specimens were in the annealed condition. The bar specimens were 13 millimeters (0.5 in.) in diameter and 38 millimeters (1.5 in.) long. Sheet specimens measured 25 millimeters (1 in.) by 50 millimeters (2 in.) by 1.6 millimeters (0.060 in.).

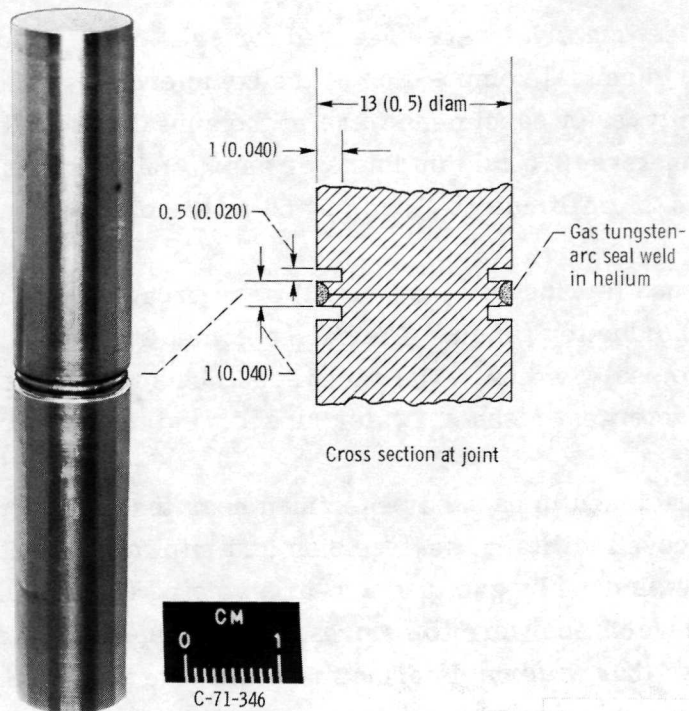
All faying surfaces (surfaces to be welded) were ground to about a 40×10^{-6} centimeter rms (16 rms) or better finish. The bar specimen faying surfaces were cleaned with acetone prior to seal welding. The sheet specimens were pickled in a 1:14, HF:HNO₃ solution, detergent cleaned, water rinsed, and then cleaned with acetone prior to seal welding.

A groove was machined in each bar specimen near the faying surface as shown in figure 1(a). The groove facilitated seal welding and minimized restraint from the seal weld. Seal welding was done by gas tungsten-arc welding (GTAW) in a helium atmosphere. Since the assemblies were to be pressed in groups of 10, each assembly had to be the same length so that uniform deformation could take place. So, the ends of the assemblies that were not auto-vac cleaned were ground flat and parallel within 0.025 millimeter (0.001 in.). The auto-vac cleaned assemblies were ground in the same manner, but after auto-vac cleaning.

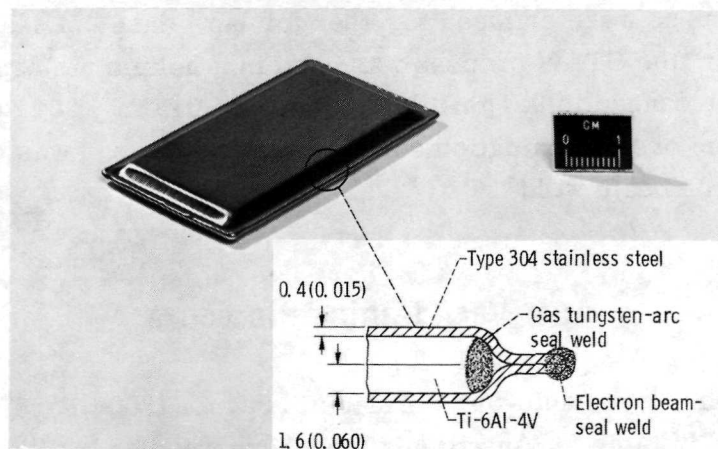
The sheet specimens were clamped together for lap joints and seal welded as shown in figure 1(b). Again, the GTAW process was used in a helium atmosphere. The sealed assemblies were then canned in 0.4 millimeter thick (0.015 in.) 304 stainless steel as shown in figure 1(b) to prevent oxidation during rolling. The can was evacuated and closed with an electron beam weld.

Auto-Vac Cleaning Procedure

The bar assemblies were auto-vac cleaned at 980° C (1800° F) for periods of 1 and 2 hours, as indicated in table I. An argon atmosphere was used, although any atmosphere suitable for heat treating Ti-6Al-4V at 980° C (1800° F) could have been used since the faying surfaces were isolated from the atmosphere by the seal weld. An auto-vac temperature of 980° C (1800° F) was used since it was high enough to cause decomposition and dissolution of oxides but was still below the beta transus (990° C or 1825° F). Some assemblies received no auto-vac cleaning and were used as control specimens.



(a) Bar assembly seal welded at periphery of faying surfaces for hot press butt welding.



(b) Sheet assembly seal welded and canned in Type 304 stainless steel for roll welding of lap joints in air.

Figure 1. - Solid-state weld assemblies for Ti-6Al-4V bar and sheet.
(Dimensions are in mm (in.).)

TABLE I. - ROOM TEMPERATURE TENSILE PROPERTIES OF HOT PRESS

BUTT WELDS IN Ti-6Al-4V BAR

Weldment designation	Auto-vac cleaning, °C/hr	Tensile test results							
		Yield strength		Tensile strength		Percent joint efficiency ^a	Elongation, ^b percent	Reduction in area, percent	Failure location
		MN/m ²	ksi	MN/m ²	ksi				
(a) As-welded - 955 ^o C/5 min/1.38 MN/m ²									
T0AW-1	None	889	129	903	131	95	4	9	Weld/parent
T0AW-3	None	882	128	950	138	100	17	44	Parent metal
T0AW-4	None	882	128	950	138	100	8	15	Weld/parent
T1AW-1	980/1	855	124	950	138	100	16	45	Parent metal
T1AW-2	980/1	867	126	957	139	100	12	18	Weld/parent
T1AW-3	980/1	855	124	957	139	100	12	21	Weld/parent
T2AW-2	980/2	860	125	944	137	100	20	48	Parent metal
T2AW-3	980/2	875	127	957	139	100	20	47	Parent metal
(b) Postheated (solution treat and age) - 940 ^o C/1/2 hr/WQ, 490 ^o C/6 hr/AC									
T0HT-2	None	1135	165	1177	171	98	0	1	Weld
T0HT-3	None	1130	164	1197	174	100	12	43	Parent metal
T1HT-1	980/1	1080	157	1184	172	99	3	2	Weld/parent
T1HT-2	980/1	1100	160	1205	175	100	11	32	Parent metal
T1HT-3	980/1	1095	159	1190	173	100	13	38	Parent metal
T2HT-1	980/2	1095	159	1197	174	100	12	37	Parent metal
T2HT-2	980/2	1110	161	1205	175	100	11	31	Parent metal

^aJoint efficiency = weld UTS/parent UTS × 100.^b2.5 cm (1 in.) gage length.

The canned sheet assemblies were similarly auto-vac cleaned in air at 980° C (1800° F) for 2 hours. Again, some assemblies were used as control specimens and were not auto-vac cleaned.

Solid-State Welding Procedure

The bar assemblies were butt welded with a hot press welder. This work was done to determine if auto-vac cleaning prior to low-deformation welding could reduce the required welding time from 60 to 180 minutes to 5 minutes. The sheet specimens were roll welded to determine if auto-vac cleaning could reduce the usual 60 percent deformation necessary to roll weld Ti-6Al-4V.

Hot press butt welding. - The bar assemblies were radiantly heated by a tantalum resistance heater in a vacuum hot press. A pressure of 2×10^{-5} torr was maintained in

the vacuum chamber during welding. The vacuum hot press was used for convenience. Any atmosphere that would not severely oxidize the Ti-6Al-4V could have been used since the weld interface was protected by the seal weld. Welding force was transmitted from a 220-kilonewton (25-ton) hydraulic press through molybdenum rams to the specimens.

The specimens were butt welded in groups of 10. Nickel foil was used on the tops of the 10 specimens to correct for slight axial misalignments between the molybdenum rams.

Both the auto-vac cleaned and nonauto-vac cleaned specimens were welded with the same welding cycle. This consisted of first soaking at a welding temperature of 955°C (1750°F) for 15 minutes under near zero pressure. A pressure of 1.38 MN/m^2 (200 psi) was then applied to each specimen for 5 minutes at temperature. A temperature of 955°C (1750°F) was selected since Ti-6Al-4V was found to have a maximum surface creep rate at this temperature (ref. 9) within the $\alpha + \beta$ region. The pressure was released and the specimens were furnace cooled. Measurements before and after welding showed that an average decrease in length of about 0.4 millimeter (0.015 in.) occurred. This represents an average deformation of 1/2 percent over the 76 millimeter (3 in.) specimen length. However, it was learned from other specimens (not in this study) that most of the deformation takes place in the material at the recesses (see fig. 1) because of the smaller cross-sectional area. This means that the actual deformation in the vicinity of the weld line was less than 1/2 percent. Of course, deformation of the asperities at the weld interface would be much greater than this, but it is not easily measured.

Roll welding. - Both the auto-vac cleaned and control specimens were roll welded at 955°C (1750°F). The specimens were soaked for 15 minutes in an air furnace at 955°C (1750°F) and transferred directly to the rolling mill. The rolls were not preheated so some loss of temperature and quenching naturally took place during rolling. Six of each type of specimen were rolled to identical deformations of 10, 15, 23, 32, 40, and 50 percent. All deformations were achieved in one pass through the rolling mill.

Evaluation Procedures

The butt welds in the bar specimens were evaluated by room temperature tensile testing and metallography. The roll lap welds in the sheet specimens were evaluated by metallography only. Bar welds were evaluated both in the as-welded condition and after a heat treatment of 940°C (1725°F)/1/2 hour/water quenched (WQ), 490°C (915°F)/6 hours/air cooled (AC) in argon. This is a standard solution treat and age (STA) heat treatment for Ti-6Al-4V. Sheet welds were evaluated only in the as-welded condition.

Mechanical testing. - Tensile specimens of the type shown in figure 2 were machined from the bar weldments. Tensile testing was done in air at a crosshead speed

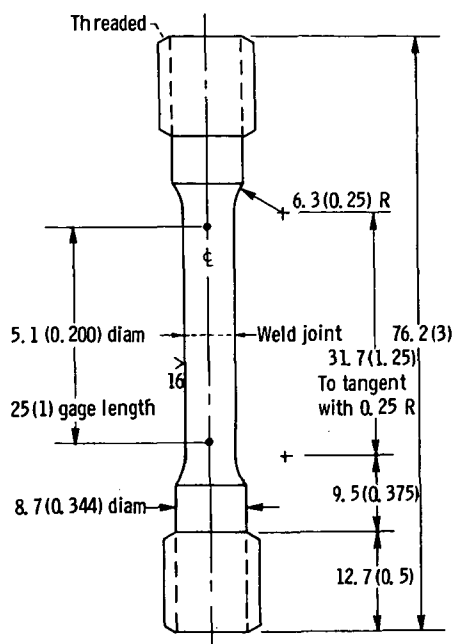


Figure 2. - Tensile specimen machined from hot press butt welds in Ti-6Al-4V bar. (Dimensions are in mm (in.).)

of 1.3 millimeters per minute (0.05 in./min) over a 25 millimeter (1 in.) gage length. Ultimate tensile strength (UTS), 0.2 percent yield strength (YS), percent joint efficiency (JE = weld UTS/parent metal UTS), elongation, reduction in area (RA), and fracture location were determined.

Although creep-rupture tests above one-half the melting point are a better evaluation method for solid-state welds (ref. 10), titanium alloys are not usually used at these high temperatures. For this reason, only room temperature tensile testing was done.

Metallography. - As-welded and postheated bar weldments were randomly selected from each group (no auto-vac, 1-hr auto-vac, and 2-hr auto-vac cleaned). Each of these specimens was sectioned, mounted, polished, and etched with a mixture of 2 parts HNO₃, 1 part HF, and 3 parts of glycerine. The metallographic specimens were inspected for the presence of a weld line, oxides, and porosity and were photographed at 250 and 750 magnifications.

The roll welded sheet specimens were also sectioned and metallographically inspected after welding. Photomicrographs were taken of the 10 and 50 percent deformed specimens.

RESULTS AND DISCUSSION

Mechanical Properties

The results of testing hot press butt welds in Ti-6Al-4V bar with and without the benefit of auto-vac cleaning are presented in table I. Figure 3 shows the three typical types of failure that occurred, as listed in table I. The "square-edge" weld failure shown on the left in figure 3 is typical of a poor solid-state weld. Partial failure in the parent material (weld/parent) indicates a better weld; the parent metal failure, away from the weld, is evidence of a high quality solid-state weld. Failure in the vicinity of weld, with all the parent metal properties (RA, elongation, YS, and UTS) is also evidence of a high quality solid-state weld.

A comparison of joint efficiency (JE) and fracture location (table I) shows that it is possible to have 100 percent JE and still have failure at least partially at the weld. Failure at the weld interface with a smooth fracture plane indicates a poor quality solid-state weld (refs. 10 to 13). The smooth fracture surface indicates that complete grain growth

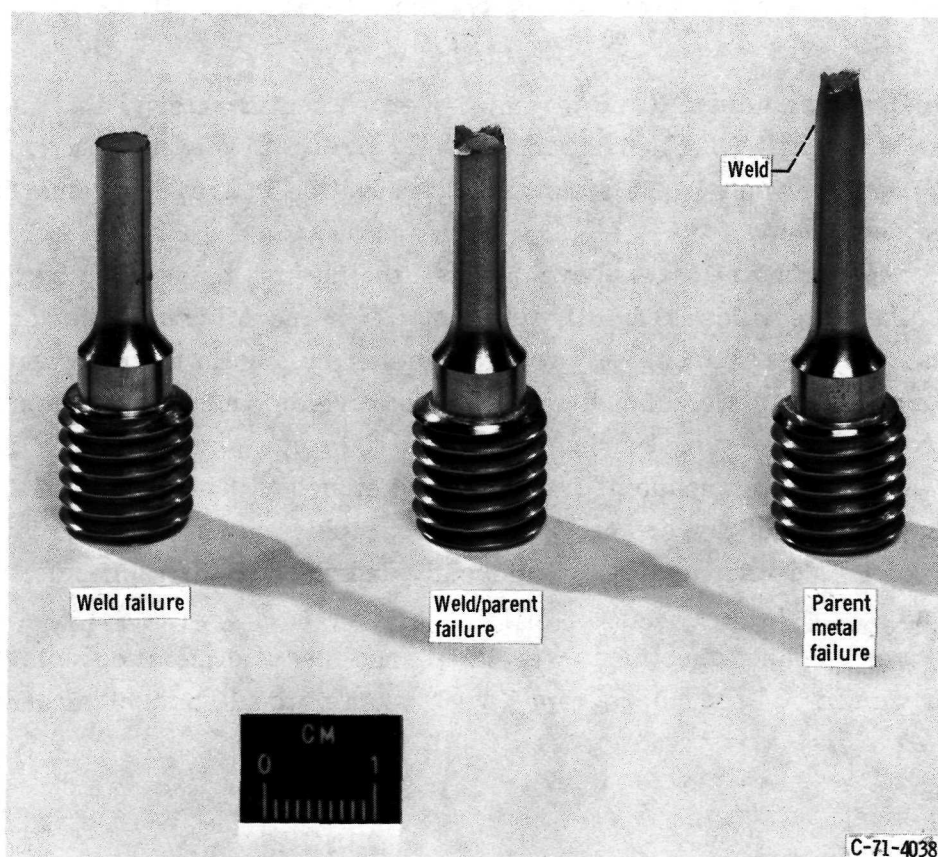


Figure 3. - Typical types of failure that occurred in hot press butt welds in Ti-6Al-4V bar during room temperature tensile tests.

across the weld interface did not occur. The weld plane has low ductility when grain growth does not occur, since it is essentially a continuous grain boundary. This low ductility is shown by low values of elongation and reduction in area (RA) in table I for weld and weld/parent failures as compared to parent metal failures. Thus, weld ductility measurements (elongation and RA) are a good indication of weld quality, while JE alone can be misleading. Room temperature bend tests are also effective in determining weld quality, but these were not conducted in this study.

A slight bulging at the weld location was noticed for some of the as-welded specimens that failed in the parent material. A difference of about 0.05 millimeter (0.002 in.) in diameter was measured between the weld and the remainder of the unfailed gage length away from the failure location. Reduction in areas of about 10 percent still occurred at these welds even though they were slightly bulged. The bulging that occurred could be due to a slightly higher concentration of oxygen near the weld from the dissolution of surface oxides. This may have caused a slight hardening of the material at and near the weld. After aging, no bulging was noted suggesting that either the oxygen was more uniformly distributed in the specimen or age hardening of the entire specimen was much greater than the slight oxygen hardening effect at the weld.

Figures 4 and 5 are graphic illustrations of the average elongation and RA values, respectively, shown in table I. Tensile strength data are not shown since JE only varied between 95 and 100 percent. Each bar on the charts represents an average value for two or three tests from each group of welds made after various amounts of auto-vac cleaning (i. e., no auto-vac, 1-hr auto-vac, and 2-hr auto-vac groups). The average values include both parent metal and weld failures. It is apparent in figures 4 and 5 that elongation and reduction in area values increase as the auto-vac cleaning time increases from 0 (no auto-vac) to 2 hours and parent metal ductility is attained. This is true whether

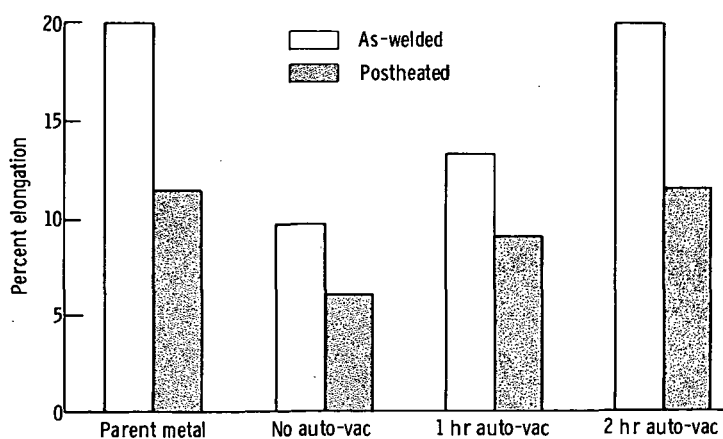


Figure 4. - Effect of auto-vac cleaning on average elongation values in Ti-6Al-4V bar hot press butt welds (values shown are average of 2 or 3 tests and included parent metal and weld failures).

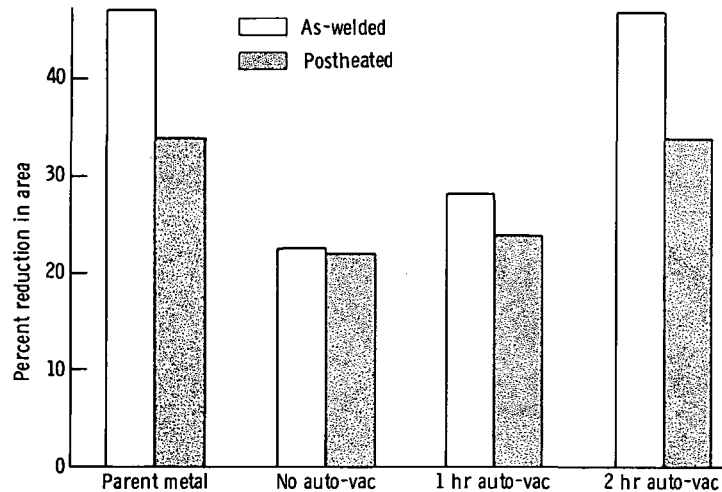


Figure 5. - Effect of auto-vac treatment on average tensile reduction in area values in Ti-6Al-4V bar hot press butt welds (values shown are averages of 2 or 3 tests and include parent metal and weld failures).

the welds are tested in the as-welded or postheated condition. While it is possible to occasionally get parent metal failure without auto-vac cleaning (see table I), auto-vac cleaning greatly increases the reliability and quality of hot press welds. With the 2-hour auto-vac cleaning treatment, the specimens fail entirely in the parent material away from the weld.

Thus, high quality hot press butt welds can be made in 5 minutes (as compared to 60 to 180 minutes required for conventional hot press welds, refs. 3 to 5) if the specimens are auto-vac cleaned prior to welding. The only atmosphere necessary for hot press welding Ti-6Al-4V is one that will prevent excessive surface oxidation at the welding temperature since the faying surfaces are protected by the seal weld.

The two most obvious advantages to auto-vac cleaning prior to hot press butt welding Ti-6Al-4V bar are the following:

- (1) Solid-state welding time can be drastically reduced for low deformation welds.
- (2) A vacuum chamber is not necessary for hot press welding since the seal weld protects the weld interface.

Metallography

Both bar and sheet weld specimens were sectioned and inspected metallographically. To determine the effect of auto-vac cleaning on the hot press butt welds in bar, specimens were evaluated from the no auto-vac, 1-hour auto-vac, and 2-hour auto-vac groups. The roll welded sheet was evaluated both with and without auto-vac cleaning

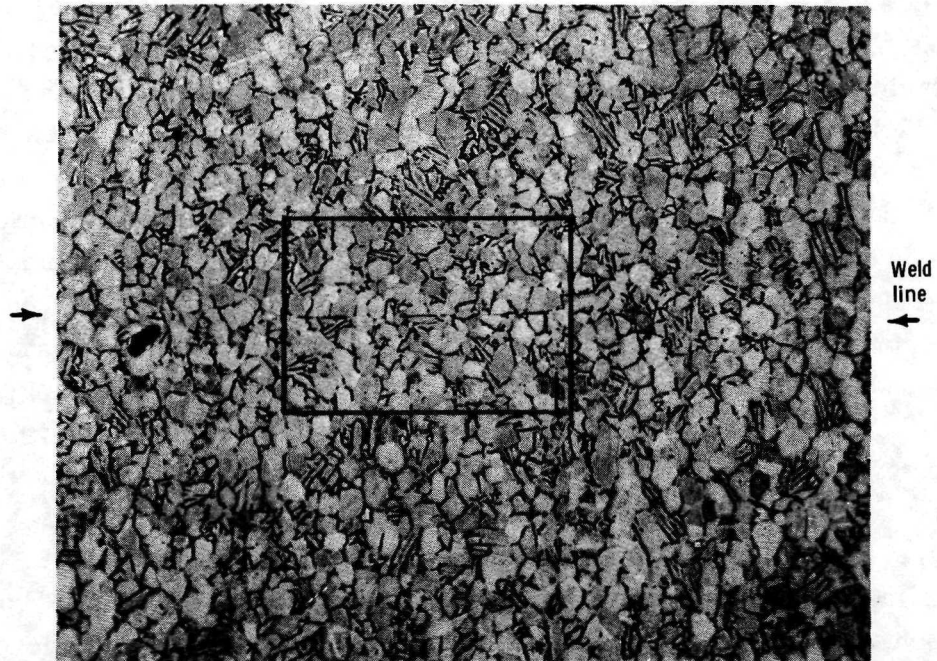
and at various deformations. These results are shown in figures 6 to 13 and summarized in the next sections.

Hot press butt welds in bar. - The microstructure of butt welds made without the auto-vac cleaning treatment are shown as-welded in figure 6 and postheated in figure 7. The as-welded microstructure (fig. 6) consists of mostly primary α and a little transformed β (acicular α). The postheated microstructure (fig. 7) is aged and consists of about half primary α , half α' (martensite), and perhaps a little, spheroidal retained β .

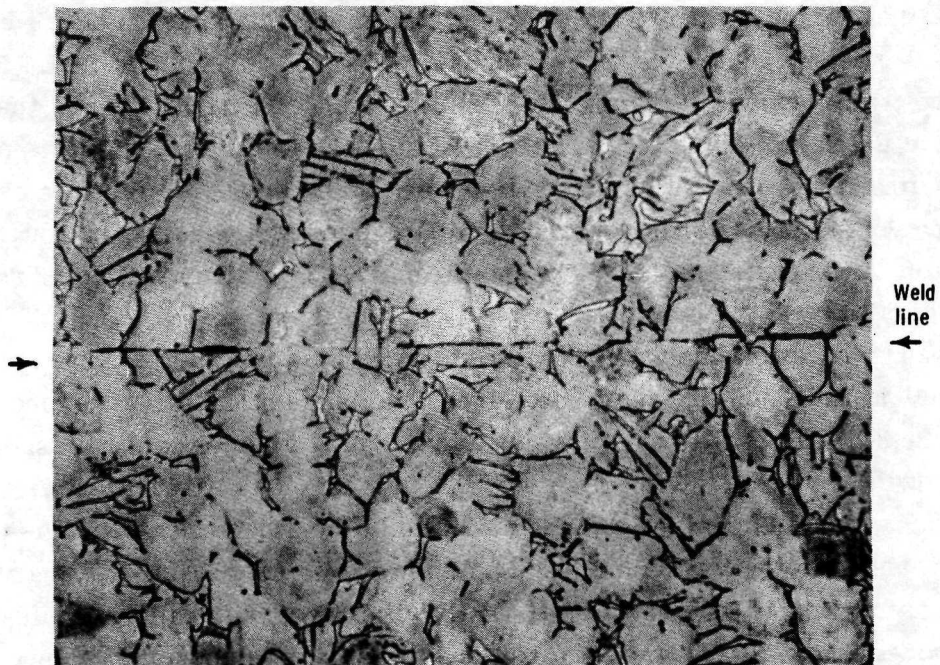
Continuous oxides (presumably mostly TiO_2 from original surface oxide films) and possibly unwelded areas are located along the weld interface (fig. 6). Postheating did not improve this condition, as shown by figure 7. The presence of a semi-continuous weld line (grain boundary), semi-continuous oxides, unwelded areas, and lack of grain growth across the weld interface are all indications of a poor quality solid-state weld. Although grain growth across the weld interface did occur in some places in the nonauto-vac cleaned specimens, the weld is far from optimum. Notice that no grain growth occurred across the weld interface where a continuous oxide was present.

Bar specimens butt welded after auto-vac cleaning at 980°C (1800°F) for 1 hour are shown as-welded in figure 8 and postheated in figure 9. The as-welded microstructure (fig. 8) consists of mostly transformed β (acicular α) and some primary α . The reason for the greater percentage of transformed β (as compared to the nonauto-vac cleaned specimen) is that during the auto-vac cleaning treatment, the specimen was heated higher into the $\alpha + \beta$ region (closer to the β transus) and thus more β formed. Even though there is more transformed β than in the nonauto-vac cleaned specimens, the mechanical properties are the same (compare parent metal failures in table I). This is probably due to both the primary α and transformed β phases being soft from furnace cooling after welding. The postheated microstructure (fig. 9) is aged and consists of roughly half primary α and half α' (martensite). The α' is more acicular as it formed from transformed β (acicular α).

The low magnification photomicrograph in figure 8(a) appears to show continuous oxides at the original weld interface. However, the higher magnification photomicrograph in figure 8(b) shows that these oxides are globular and not continuous. Also notice that grain growth has occurred across the weld interface both around and through the globular oxides. Globular oxides are then seen to be less detrimental to the quality of solid-state welds than continuous oxides. As shown in figure 9, postheating improves the weld quality and the weld interface is barely visible. Thus, auto-vac cleaning has greatly improved the quality of the solid-state weld since significant grain growth has occurred and semi-continuous oxides and/or a weld line are absent. Dissolution of surface oxide films during auto-vac cleaning allowed grain growth across the weld interface to occur during welding.

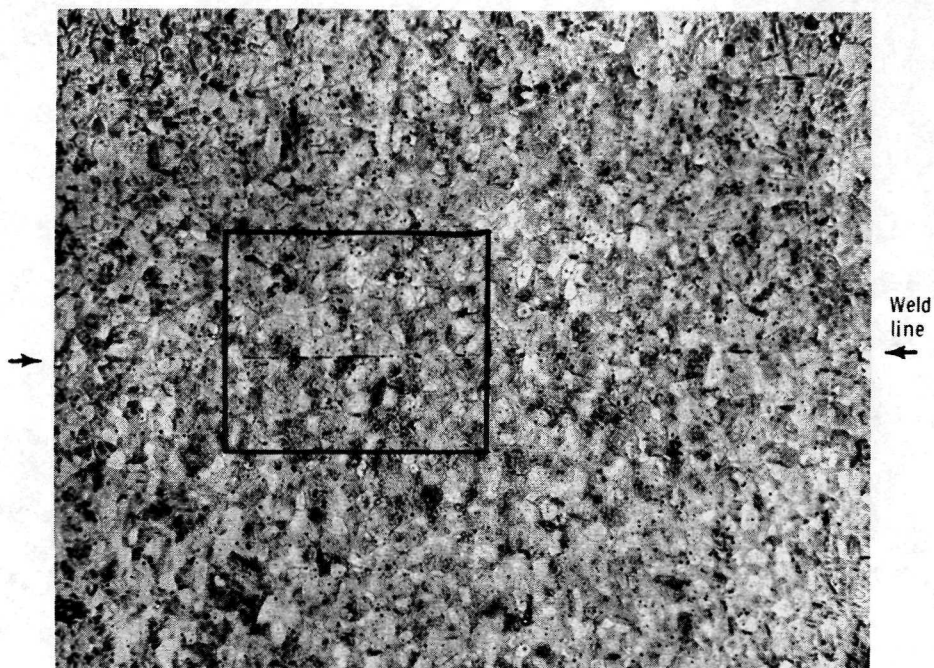


(a) Cross-section at center of weld. X250.

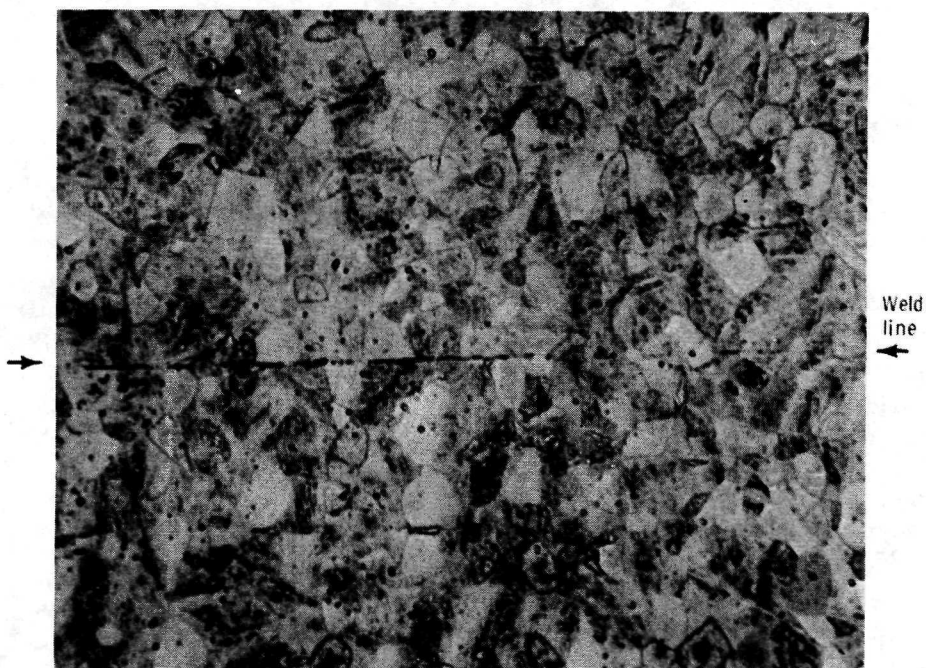


(b) Enlargement of block in (a). X750.

Figure 6. - Effect of hot press butt welding 13 millimeter (0.5 in.) diameter Ti-6Al-4V bar without benefit of prior auto-vac cleaning. Specimen is in as-welded condition - 955° C (1750° F)/ 5 min./1.38 MN/m² (200 psi).

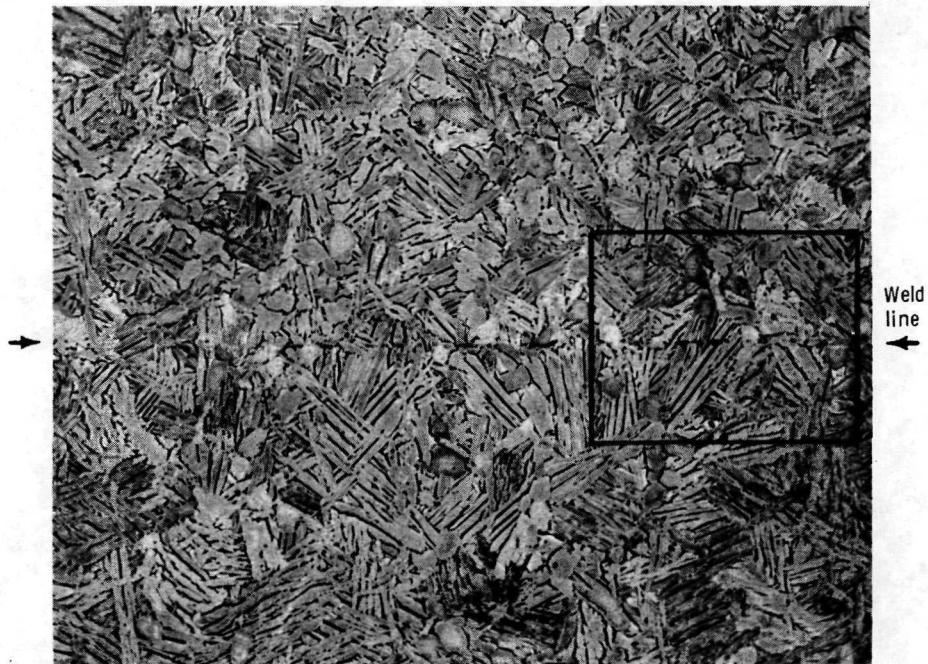


(a) Cross section at center of weld. X250.



(b) Enlargement of block in (a). X750.

Figure 7. - Effect of hot press butt welding 13 millimeter (0.5 in.) diameter Ti-6Al-4V bar without benefit of prior auto-vac cleaning. Specimen was postheated - 940°C (1725°F)/1/2 hr/WQ, 490°C (915°F)/6 hr/AC after welding.

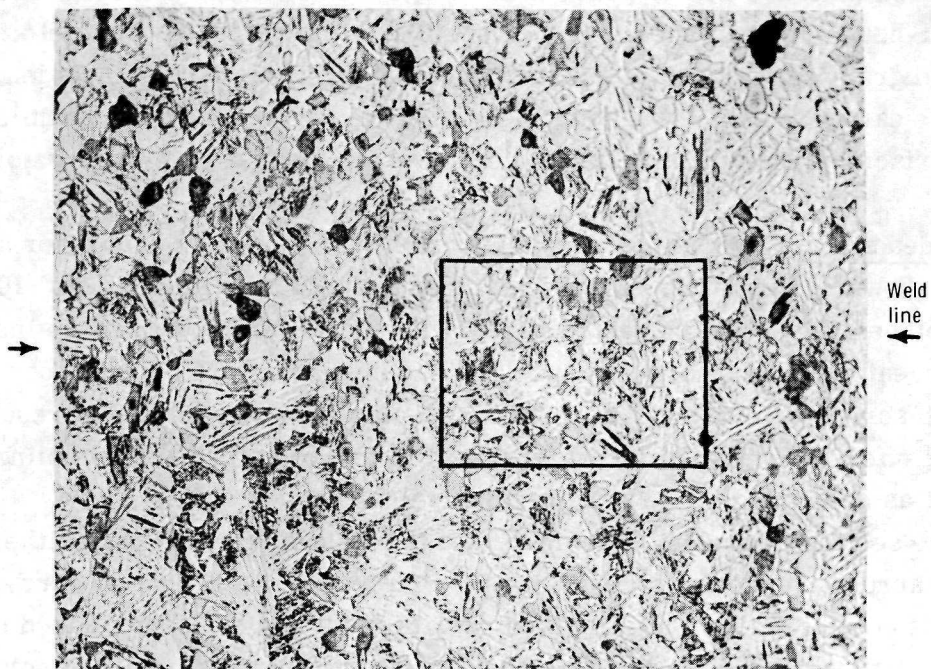


(a) Cross section at center of weld. X250.



(b) Enlargement of block in (a). X750.

Figure 8. - Effect of 1 hour at 980° C (1800° F) auto-vac cleaning prior to hot press butt welding 13 millimeter (0.5 in.) diameter Ti-6Al-4V bar. Specimen is in as-welded condition - 955° C (1750° F)/5 min./1.38 MN/m² (200 psi).



(a) Cross section at center of weld. X250.



(b) Enlargement of block in (a). X750.

Figure 9. - Effect of 1 hour at 980°C (1800°F) auto-vac cleaning prior to hot press butt welding 13 millimeter (0.5 in.) diameter Ti-6Al-4V bar. Specimen was postheated - 940°C (1725°F) / 1/2 hr/WQ, 490°C (915°F) / 6 hr/AC after welding.

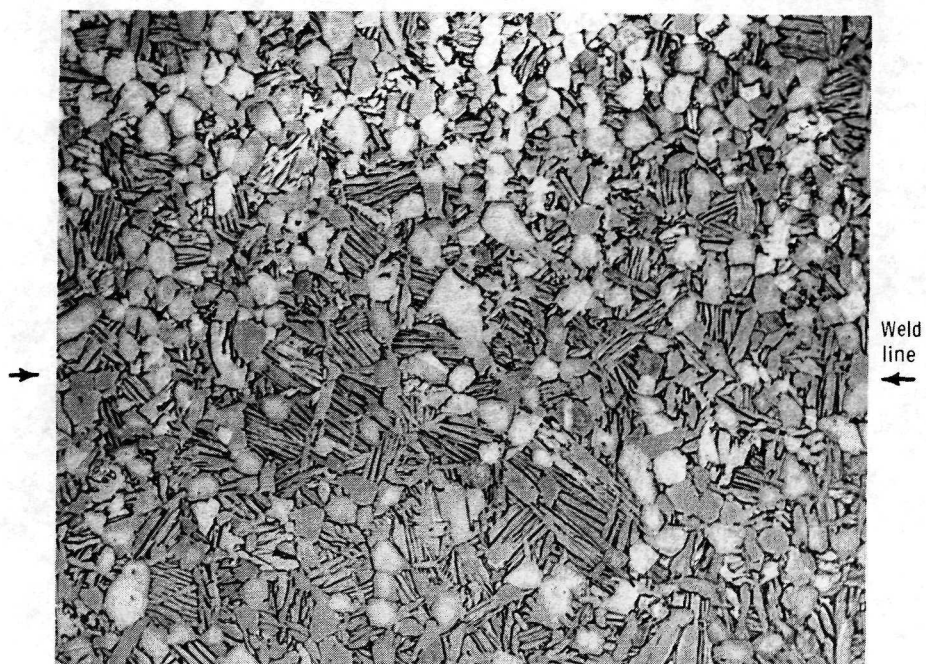
Specimens butt welded after 2 hours of auto-vac cleaning at 980°C (1800°F) are shown as-welded in figure 10 and postheated in figure 11. The microstructures are the same as the 1-hour auto-vac specimens. No oxides of any kind are present at the weld interface, and grain growth across the weld interface is complete. No evidence of the weld interface can be found. Two-hour auto-vac cleaning has provided complete dissolution of the surface oxides and made possible the formation of a high quality solid-state weld.

Roll welded sheet. - Photomicrographs of roll welds made without prior auto-vac cleaning are shown in figure 12. All the welds at the various deformations (10, 15, 23, 32, 40, and 50 percent) were inspected metallographically and found to be similar to the 10 and 50 percent welds shown in figure 12. The microstructure consists of mostly primary α with some α' (martensite). The small amount of α' probably results from the quenching effect of the rolls during roll welding and the more rapid cooling rate in the thin sheet as compared to the bar previously described.

As can be seen in figure 12, no evidence of the weld line remains in either case and grain growth across the weld interface line is complete. The 10 and 50 percent deformation roll welds and the welds made at intermediate deformations were judged to be high quality solid-state welds. The welds made at the lower deformations, especially the 10 percent weld, are quite an improvement over the typical 60 percent deformation for roll welds in Ti-6Al-4V (ref. 6).

It is felt that the seal weld (see fig. 1) around the periphery of the Ti-6Al-4V sheets made this improvement possible. During the time required for heating to the rolling temperature (955°C or 1750°F), soaking at temperature, deformation during rolling, and cooling to room temperature, the surface oxides were broken-up and dissolved in the parent material. The seal weld prevented the reformation of surface oxides while they were being broken-up and dissolved. These phenomena did not occur as completely when the nonauto-vac cleaned bar was hot press butt welded (see fig. 6) since the deformation was too low ($<1/2$ percent) to completely break-up the surface oxides. Unless the surface oxide film is dissolved by auto-vac cleaning or broken-up by large deformations (10 to 50 percent), the oxides remain at the weld interface. It is significant that once the oxide film is broken-up, it dissolves quickly.

Roll welds made after auto-vac cleaning at 980°C (1800°F) for 2 hours are shown in figure 13. Welds made at intermediate deformations were similar to the 10 and 50 percent deformation welds shown in figure 13. The microstructure consists of about one-third primary α and about two-thirds α' (martensite) from quenching effects. The greater percentage of α' and larger grain size are both due to the higher auto-vac temperature, as compared to the roll welding temperature. Complete grain growth across the weld line and elimination of the weld interface indicate high quality solid-state welds were obtained. It is evident from the results of the nonauto-vac cleaned roll welds,

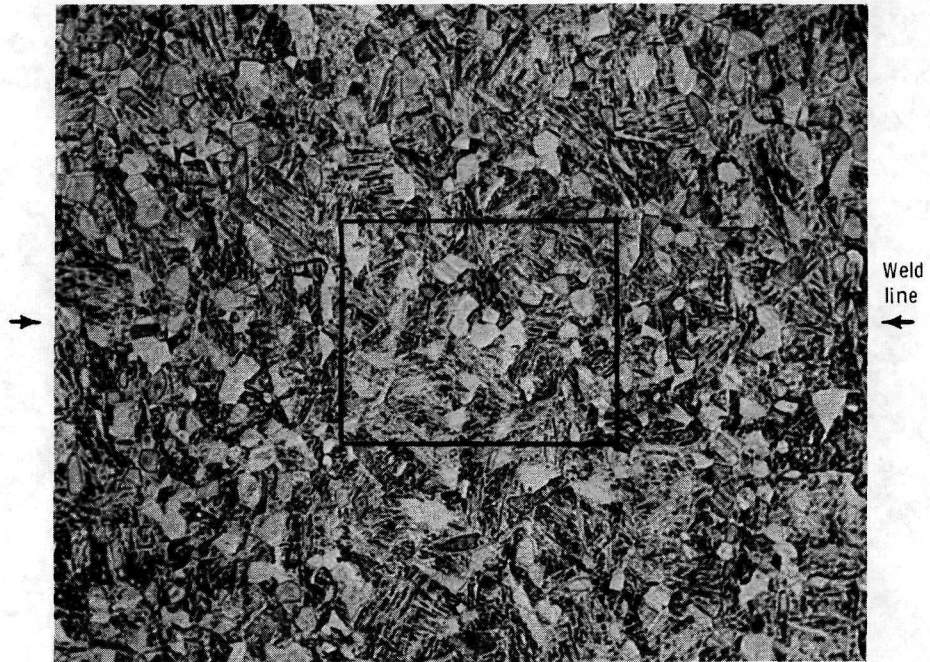


(a) Cross section at center of weld. X250.



(b) Enlargement of weld line in (a). X750.

Figure 10. - Effect of 2 hours at 980°C (1800°F) auto-vac cleaning prior to hot press butt welding 13 millimeter (0.5 in.) diameter Ti-6Al-4V bar. Specimen is in as-welded condition - 955°C (1750°F)/5 min./1.38 MN/m² (200 psi).

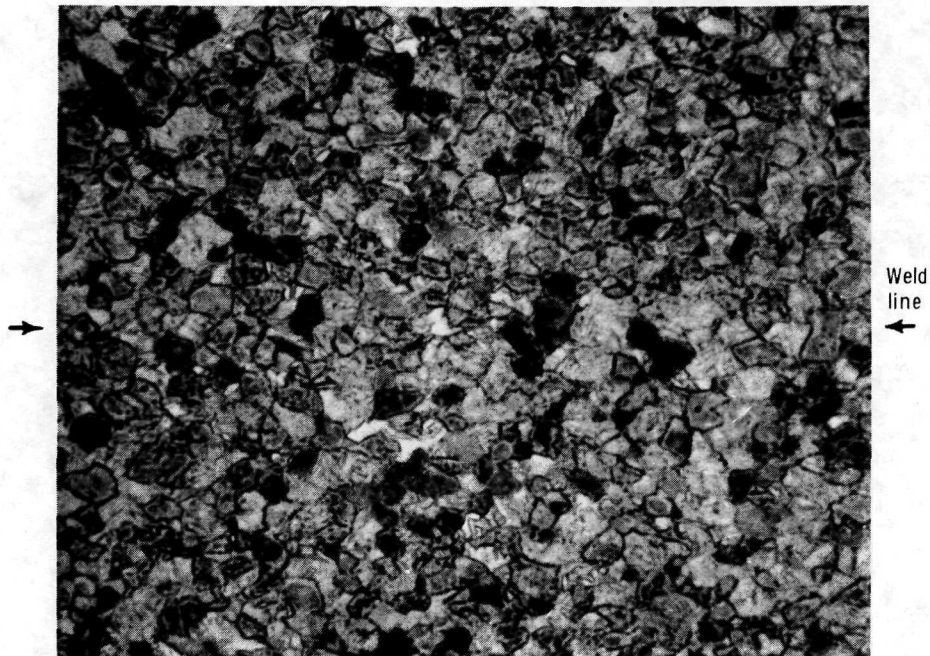


(a) Cross section at center of weld. X250.



(b) Enlargement of block in (a). X750.

Figure 11. - Effect of 2 hours at 980°C (1800°F) auto-vac cleaning prior to hot press butt welding 13 millimeter (0.5 in.) diameter Ti-6Al-4V bar. Specimen was postheated - 940°C (1725°F) 1/2 hr/WQ, 490°C (915°F) 6 hr/AC after welding.

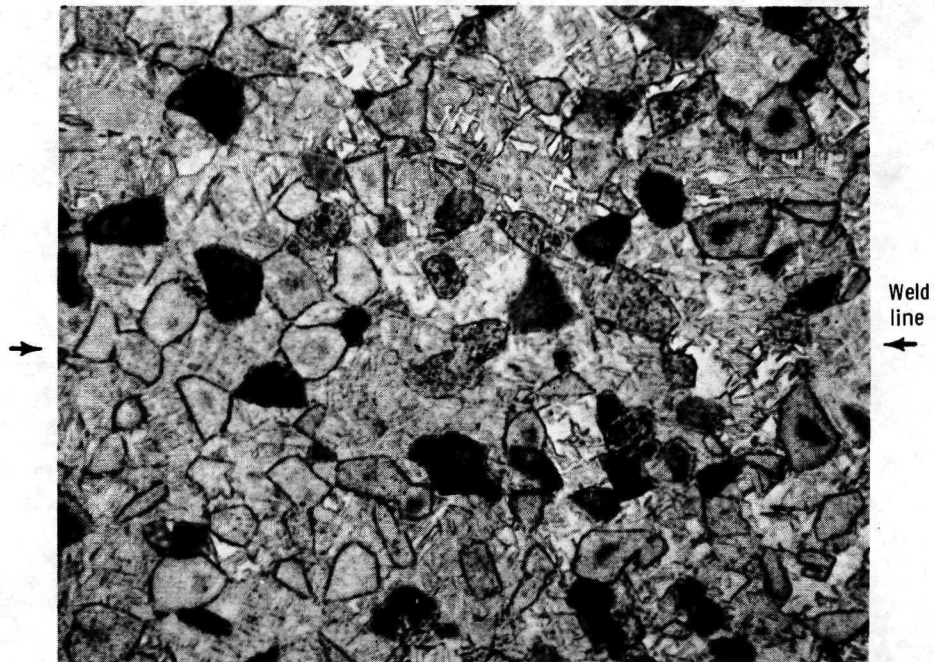


(a) 10 Percent deformation. X750.

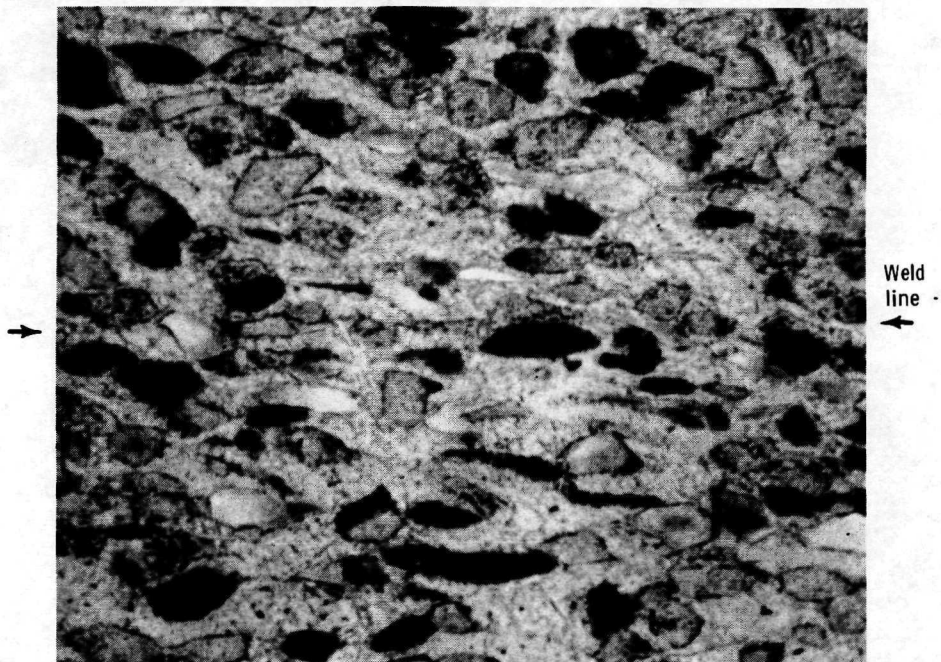


(b) 50 Percent deformation. X750.

Figure 12. - Effect of roll welding 1.6 millimeter (0.060 in.) Ti-6Al-4V sheet with prior seal welding but no auto-vac cleaning. Specimens are in as-welded condition (rolled at 955° C (1750° F) and sections were taken parallel to the rolling direction.



(a) 10 Percent deformation. X750.



(b) 50 Percent deformation. X750.

Figure 13. - Effect of 2 hours at 980°C (1800°F) auto-vac cleaning prior to roll welding 1.6 millimeter (0.060 in.) Ti-6Al-4V sheet. Specimens are in as-welded condition (rolled at 955°C (1750°F)) and sections were taken parallel to rolling direction.

however, that auto-vac cleaning prior to rolling is not necessary when deformations are 10 percent or greater.

CONCLUDING REMARKS

Auto-vac cleaning prior to welding (in addition to seal welding) is more important in low deformation (less than 1/2 percent) than high deformation (10 to 50 percent) solid-state welding. In high deformation solid-state welding, the surface oxide films are mechanically broken-up. In this state, the oxides are more easily dissolved in the parent material than in the continuous film form present in low deformation welding. The auto-vac cleaning technique should be readily applicable to most other titanium alloys since they are capable of dissolving their own surface oxides. In fact, any material capable of dissolving its surface oxides should benefit from auto-vac cleaning prior to solid-state welding.

SUMMARY OF RESULTS

Hot press butt welds were made in 13 millimeter (0.5 in.) diameter Ti-6Al-4V bar and roll welds were made in 1.6 millimeter (0.060 in.) thick sheet of Ti-6Al-4V. Some specimens were auto-vac cleaned by dissolving the surface oxides in the parent material prior to solid-state welding. The results are summarized as follows:

1. Excellent quality hot press butt welds were produced in bar by auto-vac cleaning (980°C (1800°F)/2 hr) and then hot pressing at 955°C (1750°F)/ 1.38 MN/m^2 (200 psi) for 5 minutes. Deformations of about 1/2 percent were needed. The mechanical properties of the weldments were equivalent to the parent material at room temperature. Grain growth across the weld interface completely eliminated the weld line.

2. Excellent quality roll welds were made with as little as 10 percent deformation at 955°C (1750°F). By seal welding at the periphery of the faying surfaces, excellent quality welds were made with and without intentional prior auto-vac cleaning. In the latter case, the seal weld provided auto-vac cleaning during the normal processing heat treatment. The roll welds exhibited complete elimination of the weld line by grain growth across the weld interface.

3. By using the auto-vac cleaning approach, the time required for hot press butt welding was greatly reduced, typically from as much as 60 to 180 minutes, as described in the literature, to as little as 5 minutes in this study. Roll welding was accomplished here with only 10 percent deformation compared to the 60 percent commonly used in conventional practice.

4. High strengths (>95 percent joint efficiency) were obtained for both the high-quality and poor-quality hot press butt welds. Parent metal ductility was only obtained for the high-quality welds. In this study, ductility was more meaningful in judging weld quality than strength.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 11, 1972,
114-03.

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